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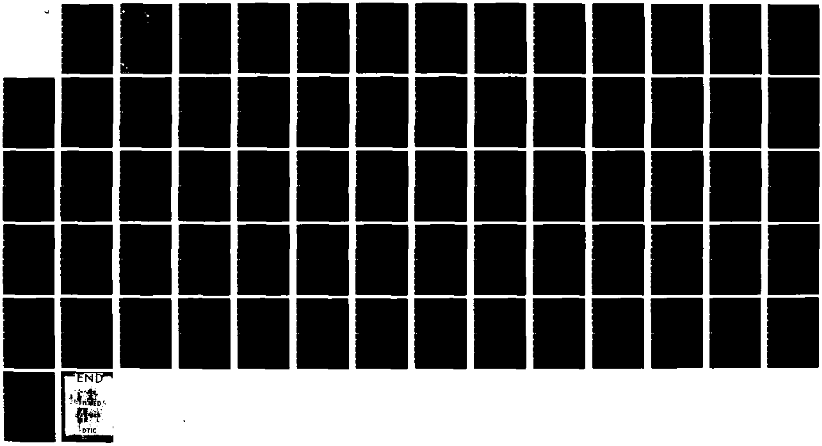

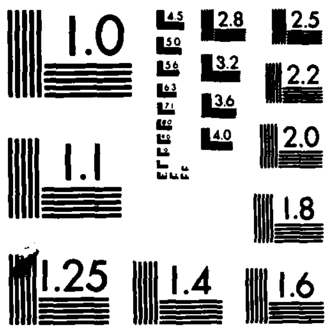
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BURIED ANTENNA ANALYSIS AT VHF

PART I: THE BURIED HORIZONTAL ELECTRIC DIPOLE

THESIS

AFIT/GEO/EE/83D-1

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Electrical Engineering

by

Jeffrey W. Burks, B.S.

2dLt USAF

Graduate Electro-Optics

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Preface

The main purpose of the thesis is to aid the education process. It is a big project and many times I lost sight of the educational value and only concentrated on completing the requirements. But as I look back, I can see how much I have learned. Even though it took a little longer than I thought, the experience and knowledge gained were well worth it.

I wish to thank my advisor, Captain Thomas W. Johnson and my sponsor, Captain Torgeir G. Fadum for their help and patience. I also want to thank my church, who gave me the encouragement I needed to get this completed. Finally, I want to praise the Lord, for through Him, all things are possible (Matthew 19;26).

Jeffrey W. Burks

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List of Symbols

AF	array factor
dΩ	differential solid angle (steradians)
D	directivity
Dm	dipole moment
E	electric field
f	frequency
G	gain
HED	horizontal electric dipole
HF	3 - 30 MHz
I	current
Idl	dipole moment for infinitesimal antenna
j	$\sqrt{-1}$
k	propagation constant
L	length of antenna
LF	30 - 300 kHz
n	index of refraction
P	power
R	distance from antenna (meters)
t	transmission coefficient for the electric field
T	transmission coefficient for power
U	radiation intensity (Watts/steradiam)
VHF	30 - 300 MHz
VLF	3 - 30 kHz

α	antenna attenuation coefficient (nepers/meter)
γ	phase factor
γ_1	loss factor
ε	permittivity
η	intrinsic impedance
θ	angle off the normal to the interface
λ	wavelength (meters)
μ	permeability
ξ	angle off horizon
π	3.1415926536
ρ	reflection coefficient for the electric field
σ	conductivity (mhos/meter)
ϕ	azimuthal angle
ϕ	phase of current at $x = 0$
ψ_1	$jk_o \cos\xi \cos\phi$
ω	radial frequency (radians/second)

<u>Subscripts</u>

a	air
ave	average
bs	Biggs and Swarm method
g	ground
in	input
o	free-space
r	relative to free-space
s	segment factor

t	transmitted
θ	θ-polarization
ϕ	ϕ-polarization
L	on antenna

Example: E_g - electric field in the ground

Abstract

Part I:

A method was developed to find the far-field radiation pattern of a buried horizontal electric dipole (HED) at 37.5 MHz. The imaginary part of the index of refraction was shown to be negligible for dry soil at this frequency so standard antenna theory and ray-optic theory :e used. The effect of the ground-air interface was modeled using t transmission coefficient and Snell's law for a dielectric interf; Because the current distribution for the buried HED depends on an. .a construction, results are shown for the far-field pattern in the air for different current distributions on the HED.

The literature on this problem was reviewed; most used the Sommerfeld or moment methods to make the same calculations. The results of one of the reports using the Sommerfeld method could be compared and were found to be similar. An extensive bibliography is included.

Part II:

The analysis was then applied to a buried antenna array. The current distribution was known and was used to calculate the far-field pattern. It was concluded that the far-field pattern is highly dependant on the current distribution. This part is classified.

I. Introduction

The theory of antennas, both in free space and above a conducting ground plane has been well defined and tested. When an antenna is buried in a medium such as the ground, the nature of the antenna is changed. The radiation pattern, current distribution, impedance and other parameters can no longer be calculated by the usual methods.

Problem

To analyze the effectiveness of a buried antenna array, the far-field pattern must be determined. The goal of this thesis is to develop a simple but accurate method to determine this pattern. The antenna array to be studied is made up of horizontal electric dipoles (HED's) and operates at 37.5 MHz. The HED's are a half-wavelength long (4 meters). The exact arrangement of the array is classified and is discussed in Part II.

Definition of the Far-Field

The far-field condition is R>>D where R is the observation distance and D is the largest dimension of the antenna. The far-field considered in this study does not include the fields in the ground. Those fields are attenuated at a rate greater than 1/R. The attenuation is dominated by the lossy effects of the ground over which it travels. The ground wave thus is insignificant for long ranges

from the antenna. Therefore in this study it is necessary to compute only the space wave for the far-field pattern. Its fields vary as a function of 1/R and travel away from the surface.

Development

A review of the applicable open literature is given in Chapter II. In this study, the radiation equation for an antenna in free space is applied to this problem using ray-optics and Snell's law at the ground-air interface. This is presented in Chapter III. Chapter IV shows the results of computations of the pattern for different parameters using the methods from Chapters II and III. Finally, Chapter V gives conclusions and recommendations for further study.

II. Literature Review

There are many studies of buried antennas in the open literature. Many of them analyze the buried HED at lower frequencies. It was difficult to apply the results to this application because the assumptions and approximations are implicit in the mathematical derivations. This is primarily due to the complexity of modeling the conductive half-space of the ground. Most of the studies reviewed here are based on Sommerfeld's method.

Sommerfeld Method

A. Sommerfeld did the initial work in this area in the early 1900's (Ref 1) and his method is followed today. A quick summary is given here before moving on to the specific articles.

The Sommerfeld method obtains an exact integral representation of the fields in adjacent conductive half-space and lossless half-space. The Helmholtz equation

$$(\nabla^2+k^2)\overline{\Pi} = -jIdl\eta/k \qquad (2\text{-}1)$$

is solved by a Fourier-Bessel transform using the appropiate boundary conditions. The fields are obtained using

$$\overline{E} = \nabla(\nabla\cdot\overline{\Pi}) + k^2\overline{\Pi} \qquad (2\text{-}2)$$

$$\overline{H} = \frac{-jk}{\eta} \times \overline{\Pi} \qquad (2\text{-}3)$$

It is fairly simple to show that equations (2-1), (2-2), and (2-3) are a solution to Maxwell's equations. The inverse Fourier-Bessel transform can then be found by an asymptotic approximation, which results from a

suitable integration in the complex plane.

Several reports have been written by Biggs and Swarm that use the Sommerfeld method (Ref 2-5). They calculate both the near and far fields from a buried HED operating at VLF (3-30 kHz) or LF (30-300 kHz). They state that propagation is limited to low frequencies because of losses, but it is not expressed as a formal limitation of the results.

Biggs (Ref 2) analyzes an inclined dipole in a conducting medium. He assumes that the depth of burial is much less than the observation distance. He also assumes that $n_g^2 >> 1$ and $k_a R/n_g^2 > 1$, where n_g is the complex index of refraction of the ground, k_a is the propagation constant of the air, and R is the observation distance.

Biggs and Swarm (Ref 3) analyze the HED in a conducting medium. The real part of the complex index of refraction is neglected, assuming

$$\frac{\sigma_g}{\omega\varepsilon_0} >> \varepsilon_r \tag{2-4}$$

This a poor approximation at VHF (30-300 MHz) as will be shown in Chapter III. Biggs and Swarm (Ref 4) give results for the HED in a lossy dielectric consisting of ice or soil. The condition in this report is that

$$R \sin\theta_a >> \frac{n_g^2}{k_a} \tag{2-5}$$

where θ_a is the angle in the air off the normal to the ground. This article is a summary of an earlier report (Ref 5) that goes into more detail on the mathematical analysis. In these last three reports (Ref 3-5), there is no limitation given for the depth of burial.

The electric fields are given as functions of polarization, distance, and position for all 4 reports (Ref 2-5) for both space waves

and ground waves. The equations are similar and are compared in Chapter IV.

Entzminger et al (Ref 6) use the same space wave equations as given in Biggs and Swarm (Ref 4.205) to calculate fields for a buried HED operating over the entire HF (3-30 MHz) range. They also study the gain and impedance of an insulated wire antenna. Several antennas of this type were constructed and buried 1 to 3 feet deep in an open field. Both the space wave and the ground wave patterns were measured for frequencies of 2 to 10 MHz. They cite excellent agreement between theoretical and measured values.

The Sommerfeld method is explained in detail by Baños (Ref 7). He calculates both the near and far fields for a HED at any depth of burial. He assumes LF operation in a conducting medium such that the real part of the complex index of refraction is negligible. (A special note - 'n' in his book represents the reciprical of the index of refraction for the ground.)

Vaziri (Ref 8) uses the Sommerfeld method to analyze all four Hertzian dipoles, horizontal and vertical electric dipoles and horizontal and vertical magnetic dipoles, as buried antennas. Rather than obtaining the inverse Fourier-Bessel transform asymptotically, he evaluates the inversion integral by direct numerical integration in the complex plane. His Fortran program is given but its limitations are not discussed. Its purpose is to calculate the E and H-fields at any polarization at any observation point in a certain plane. For the HED, this plane is the vertical plane parallel to and intersecting the dipole. Above ground antennas can also be modeled by switching the medium constants around.

Experimental results are given for a horizontal traveling wave antenna buried 40 centimeters deep in an open field and operated at 144 MHz. The theory and measurements agreed within the "acceptable accuracy". Also, Baños's approximations are computed in the program and are also found to agree with the measurements in most cases. This is surprising because they are not supposed to be valid for such high frequencies.

King, Sandler, and Shen (Ref 9) use the Sommerfeld method to find the fields in the ground for a buried HED. The fields in the air are not examined. Both a complex permittivity and complex conductivity are used to calculate the propagation constant of the ground, k_g.

King and Shen (Ref 10) use the Sommerfeld method to calculate the fields directly above a buried HED to determine its environmental hazard. Graphs are given for the fields at a height z from a HED buried 0.175 meters in dry soil and operated at 144 MHz. But the values given for conductivity ($\sigma_g = 4 \times 10^{-5}$ mhos/meter) and permittivity ($\varepsilon_g = 4\varepsilon_0$) do not satisfy the condition that

$$\frac{k_a}{k_g} \leq 0.05 \text{ (ie } n_g \geq 20) \tag{2-6}$$

where

$$k_a = \omega(\mu_0\varepsilon_0)^{\frac{1}{2}} \tag{2-7}$$

$$k_g = (\omega^2\mu_0\varepsilon_g + j\omega\mu_0\sigma_g)^{\frac{1}{2}} \tag{2-8}$$

For these values of σ_g and ε_g, the imaginary part of k_g is at least an order fo magnitude smaller than the real part for frequencies above 2 MHz. So at 144 MHz,

$$k_g \simeq (4\mu_0\varepsilon_0)^{\frac{1}{2}} \tag{2-9}$$

Therefore,

$$\frac{k_a}{k_g} = 0.5 \tag{2-10}$$

which is a factor of 10 too big.

A different approach is given by Bannister (Ref 11) that combines the Sommerfeld method with image theory. He gives equations for the far-field and requires that $n_g^2 > 15$. He also requires that the observation distance be at least three times greater than the burial depth. A few results are given for the HF range, but there seems to be no other restrictions on frequency.

In all the reports mentioned so far (Ref 2-11), the current distribution on an actual antenna is not analyzed. Calculations are performed only for an infinitesimal dipole,with a uniform current distribution. Entzminger et al (Ref 6.7) do replace the dipole moment, Idl, by a general dipole moment,

$$Dm = \int_{-L/2}^{L/2} I(x)\ \exp(jk_o x\cos\phi)dx \tag{2-11}$$

but does not evaluate it. Also, this dipole moment is only valid for the fields at the surface.

Moment Method and Others

The moment method has been applied to the buried antenna problem to find the pattern without knowing the current distribution. Miller and Burke (Ref 12) and Miller and Deadrick (Ref 13) use the moment method on the thin wire integral equations along with a transmission coefficient for a buried HED. They report their results to be consis-

tent with the Sommerfeld method. It seems to be applicable to VHF but the mathematics are outside the scope of this thesis. Numerical results are given in Reference 13 for a buried wire antenna operated at frequencies of 1 MHz and 10 MHz.

Brammer (Ref 14) presents the moment method and a transmission line method as two ways to calculate the fields for a buried insulated wire antenna operated at 2 to 16 MHz. The methods and assumptions are not described very well but he reports them to be consistent.

Many other references to buried antennas were found but only the ones that are discussed here apply directly to the problem of finding the far-field pattern of a buried HED. Some of these other references are listed (Ref 18-43) for future reference.

III. Perfect Dielectric Method

If the ground is assumed to be a perfect or slightly lossy dielectric ($\varepsilon'' \ll \varepsilon'$), standard ray-optics and antenna theory can be used to calculate the far-field antenna pattern for a buried antenna. Table III-1 shows the complex index of refraction,

$$\tilde{n}_g = \sqrt{\varepsilon_r - j\frac{\sigma_g}{\omega\varepsilon_0}} \qquad (3\text{-}1)$$

for different soils with $\omega = 2\pi \times 37.5$ MHz. For dry conditions, the imaginary part of $\tilde{n}_g$ can be neglected and the slightly lossy dielectric assumption holds. For these values and at this frequency, the assumption is not very good for wet soils.

Assuming dry soil, the field distribution of the buried antenna can now be calculated by standard techniques. The method in Stutzman and Thiele (Ref 15.25) is modified to account for the air-dielectric interface. The E-field at some far-field point Q for a dipole of length L on the x-axis as shown in figure III-1 is

$$\bar{E}_g = -\frac{j\omega\mu_g}{4\pi R}(\cos\theta_g\cos\phi\hat{\theta} - \sin\phi\hat{\phi})Dm\ \exp(-jk_gR) \qquad (3\text{-}2)$$

where

$$Dm = \int_0^L I(x)\exp(jk_g x\sin\theta_g\cos\phi)dx \qquad (3\text{-}3)$$

$$k_g = n_g k_o \qquad (3\text{-}4)$$

When the half-space above z=h is replaced by air, the radiation observed at point Q is different due to the following:

Reference	Soil moisture content	Analysis frequency	Dielectric constant ϵ_r	Conductivity (mhos/m) σ_g	Complex index of refraction (at 37.5 MHz) $\hat{n}_g$
Biggs and Swarm (Ref 3:206)	not given	LF	10	0.0005	10 - j0.24
Entzminger *et al* (Ref 6:45-48)	wet?	10 MHz	60	0.03	60 - j14.0
King and Shen (Ref 10:1052)	dry	144 MHz	4	0.00004	4 - j0.019
Corvus (Ref 46:33)	dry	HF, VHF	9	0.001	9 - j0.48
	wet	HF, VHF	25	0.01	25 - j4.8
Burke *et al* (Ref 47:99)	dry	HF, VHF	9	0.005	9 - j2.4
	wet	HF, VHF	20	0.05	20 - j24

Table III-1. The Complex Index of Refraction at 37.5 MHz for Different Soils.

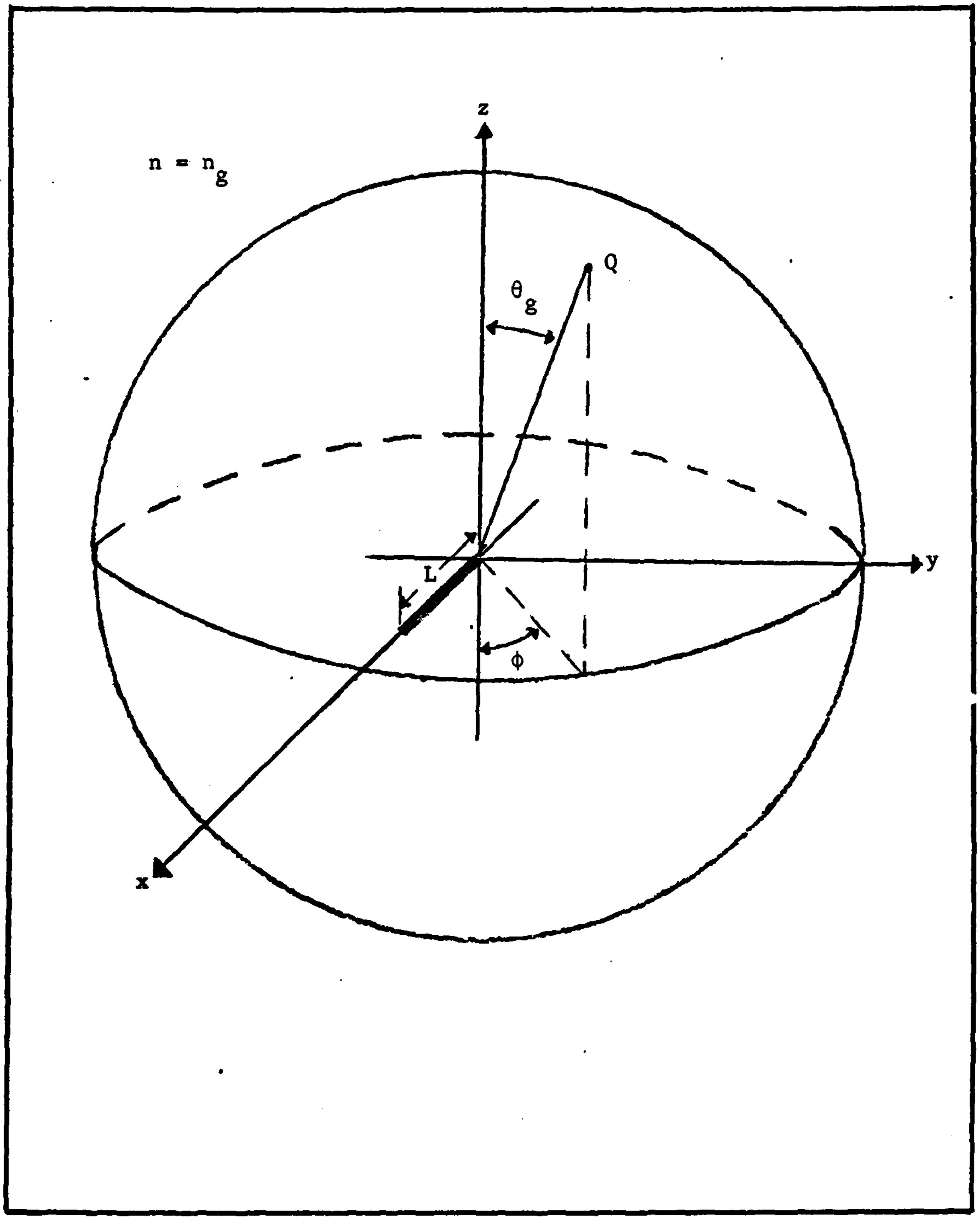

Figure III-1. Orientation of the HED in an Infinite Dielectric Medium.

1) Only part of the radiation incident on the interface is transmitted; the rest is reflected.

2) Refraction changes

a) the direction of the radiation,

b) the dipole moment, Dm, and

c) the radiation intensity, U_g.

The Fresnel transmission coefficient (Ref 16.74), t, is used to calculate the part of the field that is transmitted such that

$$E_{\theta t} = t_\theta E_{\theta g} \tag{3-5}$$

$$E_{\phi t} = t_\phi E_{\phi g} \tag{3-6}$$

For the θ-polarized E-field,

$$t_\theta = \frac{2n_g \cos\theta_g}{n_a \cos\theta_a + n_a \cos\theta_g} \tag{3-7}$$

and for the ϕ-polarized E-field,

$$t_\phi = \frac{2n_g \cos\theta_g}{n_a \cos\theta_a + n_g \cos\theta_g} \tag{3-8}$$

The effect of refraction is described by Snell's law

$$n_a \sin\theta_a = n_g \sin\theta_g \tag{3-9}$$

Using equations (3-4) and (3-9) in (3-3) results in

$$Dm = \int_0^L I(x)\ \exp(jk_o x \sin\theta_a \cos\phi) dx \tag{3-10}$$

which is the same dipole moment as for an HED in free space. The ground has no effect because all rays at a certain angle travel the same distance through the ground as shown in figure III-2. Because array theory is derived from the free space dipole moment, this also means that conventional array theory can be used in analyzing buried

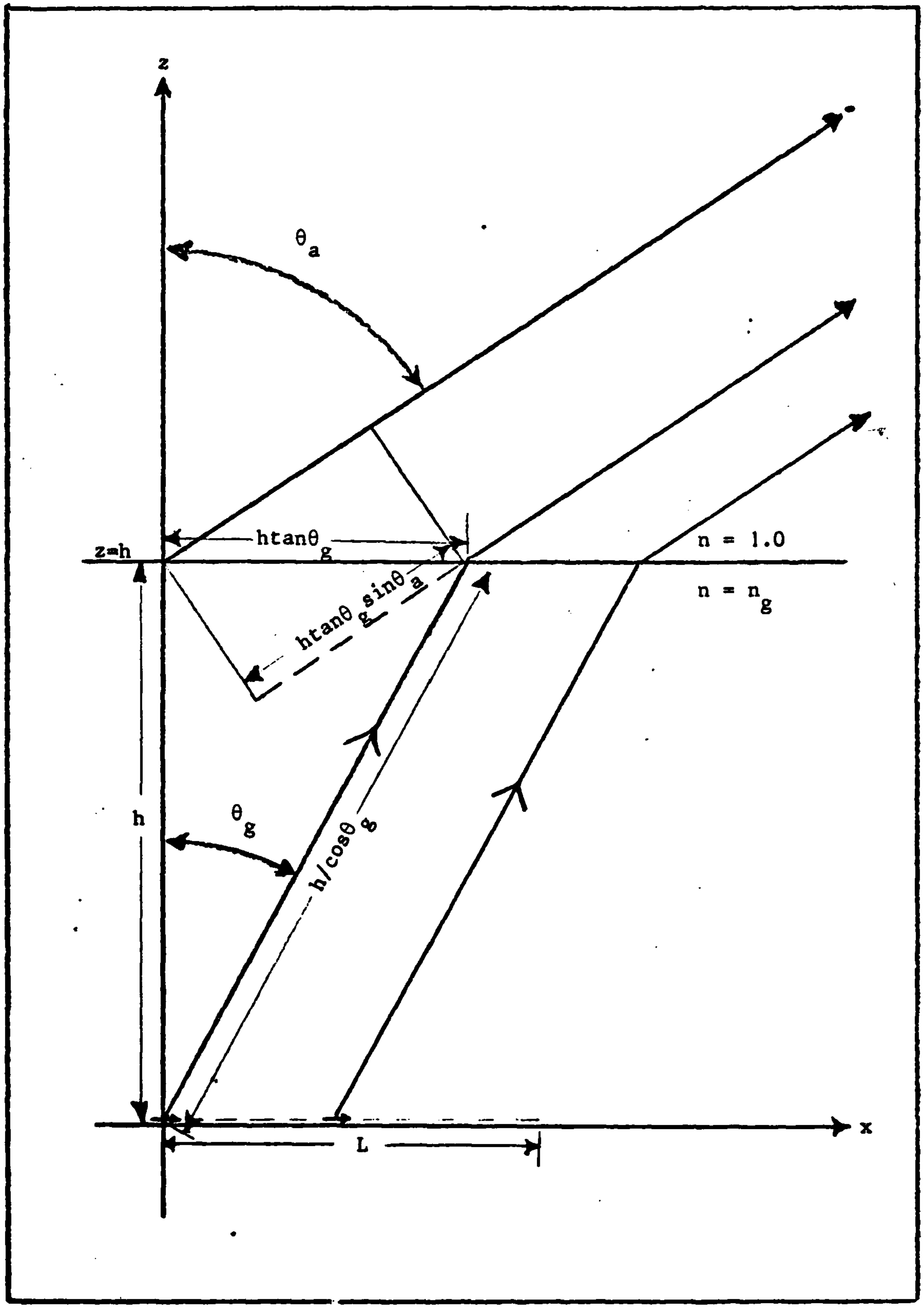

Figure III-2. Orientation of the HED Showing the Air-dielectric Interface and Ray Paths.

antenna arrays.

The phase factor, $\exp(-jk_gR)$ in equation (3-2) changes slightly to

$$\gamma = \exp\left(-\frac{jk_o n_g h}{\cos\theta_g} - jk_o(R - h\tan\theta_g \sin\theta_a)\right) \qquad (3\text{-}11)$$

The wave travels a distance $h/\cos\theta_g$ through the ground, but the distance it travels through the air is shortened by $h\tan\theta_g \sin\theta_a$ as shown in Figure III-2. Equation (3-11) is then simplified to

$$\gamma = \exp(-jk_oR - jk_o n_g h\cos\theta_g) \qquad (3\text{-}12)$$

by using Snell's law, a trigonometric identity, and equation (3-4).

If the losses and near-fields are ignored, then the power just above the surface in the solid angle $d\Omega_g$ must be equivalent to the power in the far-field in the solid angle $d\Omega_a$, such that

$$U_a(\theta_a,\phi)d\Omega_a = U_t(\theta_g,\phi)d\Omega_g \qquad (3\text{-}13)$$

where

$$d\Omega_a = \sin\theta_a d\theta_a d\phi \qquad (3\text{-}14)$$

$$d\Omega_g = \sin\theta_g d\theta_g d\phi \qquad (3\text{-}15)$$

Differentiating Snell's law yields

$$d\theta_g = \frac{n_a\cos\theta_a}{n_g\cos\theta_g}\, d\theta_a \qquad (3\text{-}16)$$

and substituting this and Snell's law into equation (3-15) results in

$$d\Omega_g = \frac{n_a}{n_g}\sin\theta_a \frac{n_a\cos\theta_a}{n_g\cos\theta_g}\, d\theta_a d\phi = \frac{n_a^2\cos\theta_a}{n_g^2\cos\theta_g}\, d\Omega_a \qquad (3\text{-}17)$$

From equations (3-13) and (3-17)

$$U_a(\theta_a,\phi) = U_t(\theta_g,\phi)\,\frac{n_a^2\cos\theta_a}{n_g^2\cos\theta_g} \qquad (3\text{-}18)$$

From Poynting's theorem, the radiation intensity is

$$\overline{U} = \mathrm{Re}(\tfrac{1}{2}\overline{E} \times \overline{H}^{*})R^2\hat{R} \tag{3-19}$$

In free space or air, $\overline{E}$ and $\overline{H}$ are perpendicular and $H = E/\eta_0$, therefore,

$$U_t(\theta_g,\phi) = \frac{1}{2\eta_0}\left|E_t\right|^2 R^2 \tag{3-20}$$

Thus, the far-field pattern is

$$U_a(\theta_a,\phi) = \frac{t^2}{2\eta_0}\left|E_g\right|^2 \frac{n_a^2\cos\theta_a}{n_g^2\cos\theta_g} R^2 \tag{3-21}$$

So from equations (3-2), (3-5), (3-7), and (3-10), the far-field pattern for the θ-polarized E-field is

$$U_a(\theta_a,\phi) = \left(\frac{2n_g\cos\theta_g}{n_g\cos\theta_a + n_a\cos\theta_g}\right)^2\left(\frac{1}{2\eta_0}\right)\left(\frac{-j\omega\mu_g}{4\pi}\cos\theta_g\cos\phi\right)^2\frac{n_a^2\cos\theta_a}{n_g^2\cos\theta_g}$$

$$\times\left(\int_0^L I(x)\,\exp(jk_o\sin\theta_a\cos\phi)dx\right)^2 \tag{3-22}$$

where $\mu_g = \mu_o$.

Results using this equation will be shown in the next chapter after a brief look at the results from the Sommerfeld method.

IV. Results

As seen from the preceeding two chapters, there are several ways of analyzing the buried antenna. The next step is to apply these methods for this specific case and compare the results. It would be even better to compare them to actual measurements, but these are unavailable at this time.

Of the three main methods; the moment method (Ref 12,13), the Sommerfeld method (Ref 2-11), and the dielectric method, only the Sommerfeld method and dielectric methods are discussed here. The moment method looks promising but is better left for another study.

Biggs and Swarm (Ref 4) and Vaziri (Ref 8) use the Sommerfeld method to give solutions that seem the most applicable here. Many of the other solutions were not usable because of the specific assumptions or conditions. Usually, the analyses applied only for lower frequencies, and hence, the index of refraction is assumed to be greater than what it is at VHF.

Vaziri

The Fortran program written by Vaziri looked very promising as mentioned before. It was typed into AFIT's Vax 11/780 computer line by line as given in his dissertation. Some of it was excluded because the code given for the vertical electric dipole and magnetic dipoles was not needed. At first, the program would not compile. No syntax or error message was generated during assembly. Only when the multiple

RETURN's were taken out of the FNC function did the program compile without generating a compiler error. Evidently, there were more RETURN's in the FNC function than the Vax could handle. When these were reduced by deleting more unneeded code, the program compiled. This version is shown in Appendix A for future reference.

When it was run with $n_g = 3.0$, $\sigma_g = 0.005$ mhos/meter, and the burial depth, h = 0.5 meters, the output was obviously wrong. For a distance of 50 meters, the antenna pattern increases toward infinitity at an angle of 35^0 off the horizon. For greater distances, the angle where the pattern goes to infinity is decreased. The code was examined several times but the error was not found.

Biggs and Swarm

Biggs and Swarm give the closed form solution of the far-field θ-polarized E-field as

$$E_{bs} = \frac{j}{R} 60k_o Idl \cos\phi \frac{\cos\theta_a \sqrt{\tilde{n}_g^2 - \sin^2\theta_a}}{\tilde{n}_g \cos\theta_a + \sqrt{\tilde{n}_g^2 - \sin^2\theta_a}}$$

$$\cdot \exp(jk_o R + jk_o h \sqrt{\tilde{n}_g^2 - \sin^2\theta_a}\ ) \qquad (4\text{-}1)$$

They have assumed that $k_o R/n_g^2 >> 1$. This is met when R > 100 meters for $n_g = 3.0$. Using the same argument as for the dielectric method, the imaginary part of $\tilde{n}_g$ can be neglected at this frequency. The radiation intensity can be calculated from

$$U_{bs} = \frac{1}{2\eta} \left|E_{bs}\right|^2 R^2 \qquad (4\text{-}2)$$

(see equation (3-20)). Then from Snell's law and a trigonometric identity

$$n_g \cos\theta_g = \sqrt{n_g^2 - \sin^2\theta_g} \qquad (4\text{-}3)$$

it can easily be shown that

$$U_{bs} = U_a \frac{\cos\theta_a}{\cos\theta_g} \tag{4-4}$$

where U_a is the result from the dielectric method, equation (3-22), with dipole moment Idl.

This seems to indicate that these two methods of calculating the E-fields are compatible. The results are in complete agreement at $\theta_a = 0^0$ (directly overhead), but diverge as the angle increases toward the horizon. For $n_g \geq 3$, $\cos\theta_g \simeq 1$ for all θ_a, so the difference is mainly a factor of $\cos\theta_a$. The equations given in the other reports by Biggs and Swarm (Ref 2,3,5) as well as King and Shen (Ref 10) also give the same answer for $\theta_a = 0^0$.

Computer Program for the Dielectric Method

The Fortran program shown in Appendix B was developed from the equations of Chapter III and used to calculate the radiation pattern for a buried half-wave HED. Although the program will calculate both θ and ϕ-polarizations, only results for the θ-polarization are shown here for simplicity. No new information would be gained by looking at the ϕ-polarization but it might be important in a later study so the equations were left intact.

The integration to calculate the dipole moment (equation (3-10)) is performed numerically because the effect of burial on the current distribution is not known. In this way, different current distributions can be tested to see what pattern is generated.

The Uff subroutine (page B-3) can be used to calculate the far-field radiation intensity in any direction in the air above a buried

HED. Both U_a and U_{bs} are calculated given the index of refraction, θ_a, ϕ, and the parameters for the current distribution. The program should be applicable to other frequencies by changing the value of FQ (frequency) as long as the imaginary part of the index of refraction is negligible at that frequency.

Calulated Patterns

The results shown here are for the radiation intensity in the x-z plane. A sinusoidal current distribution

$$I(x) = \sin(k_r k_o x) \exp(-\alpha x) \qquad (4\text{-}5)$$

was used to model the current on a 4-meter-long wire antenna.

Figure IV-1 shows the pattern for the half-wave HED, both in free-space and buried. The buried antenna radiates a much more constant pattern. Figure IV-2 shows the change in the pattern for the range of soil dielectric constants. The radiation intensity near the horizon does not change very much, but these do not take into account how the current distribution might change. Here, the current distribution was held constant, but in the real world the current distribution may change drastically.

Figures IV-3 and IV-4 show what happens as the current distribution is changed. In Figure IV-3, the current has been attenuated by changing the value of α in equation (4-5). This does not change the pattern except to lower it as the attenuation is increased. As the propagation constant is changed, the pattern changes much more, although it is still the same near the horizon as shown in Figure IV-4.

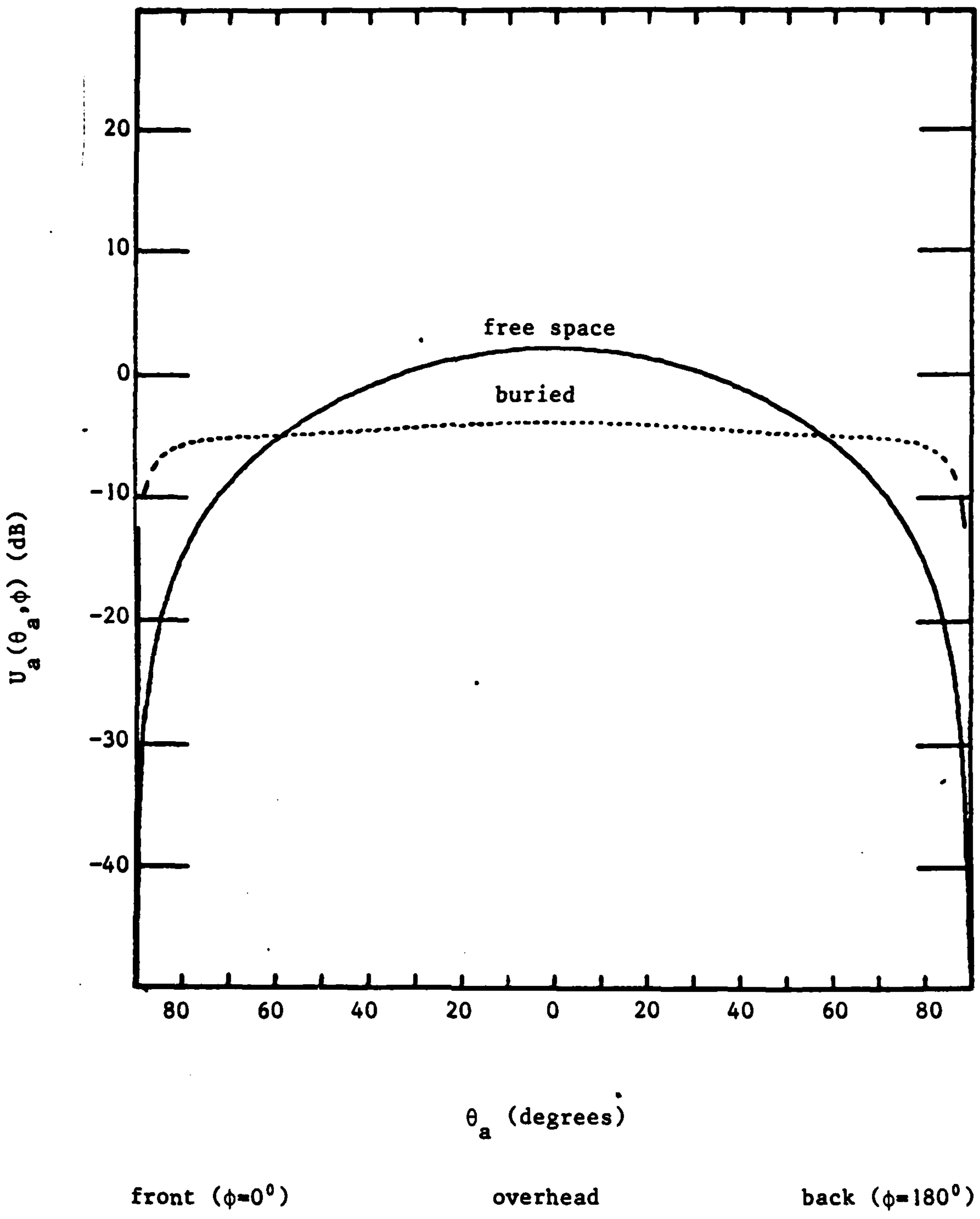

Figure IV-1. Calculated Pattern for the HED, Both In Free Space and Buried.

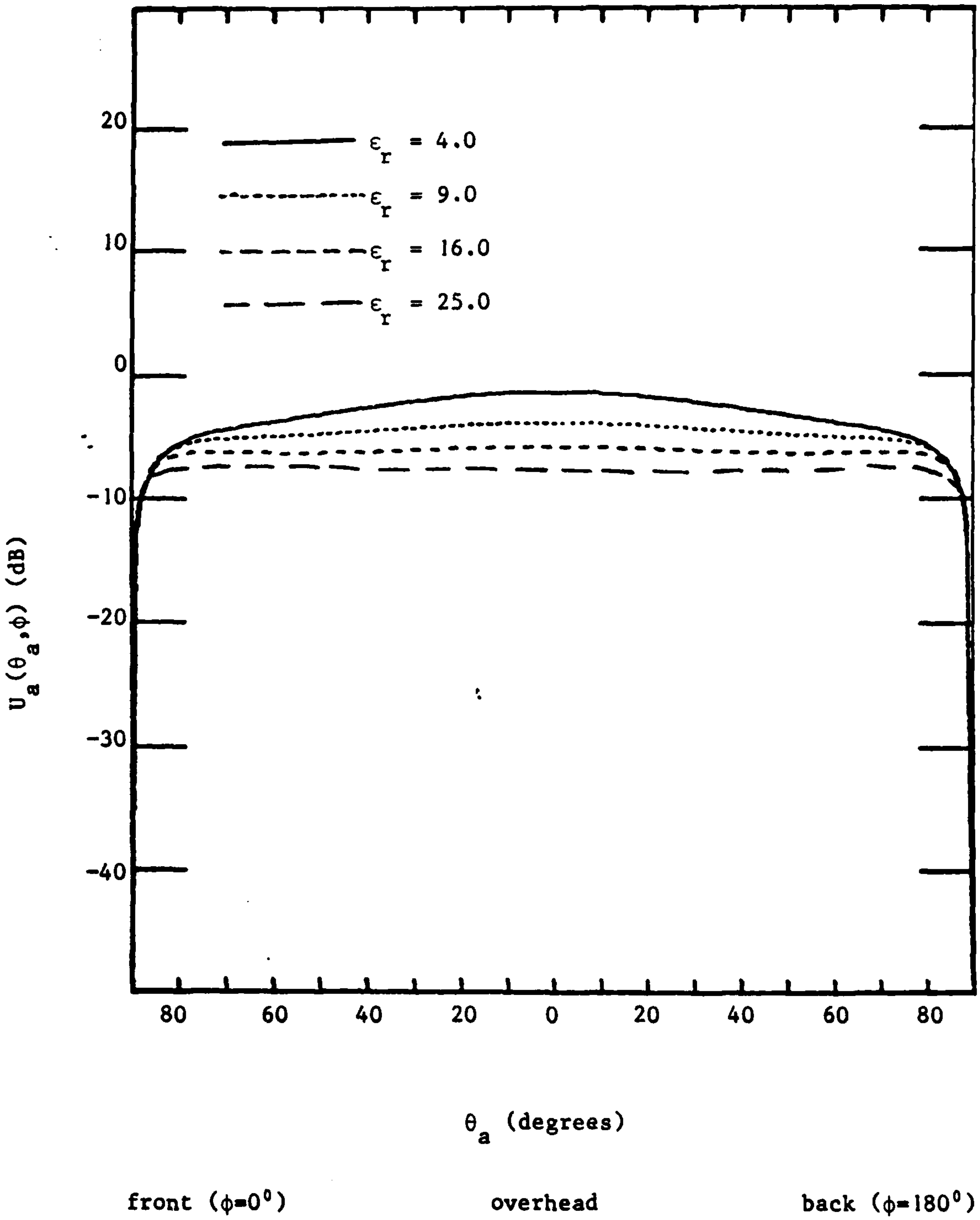

Figure IV-2. Calculated Pattern for the Buried HED With Different Soil Dielectric Constants.

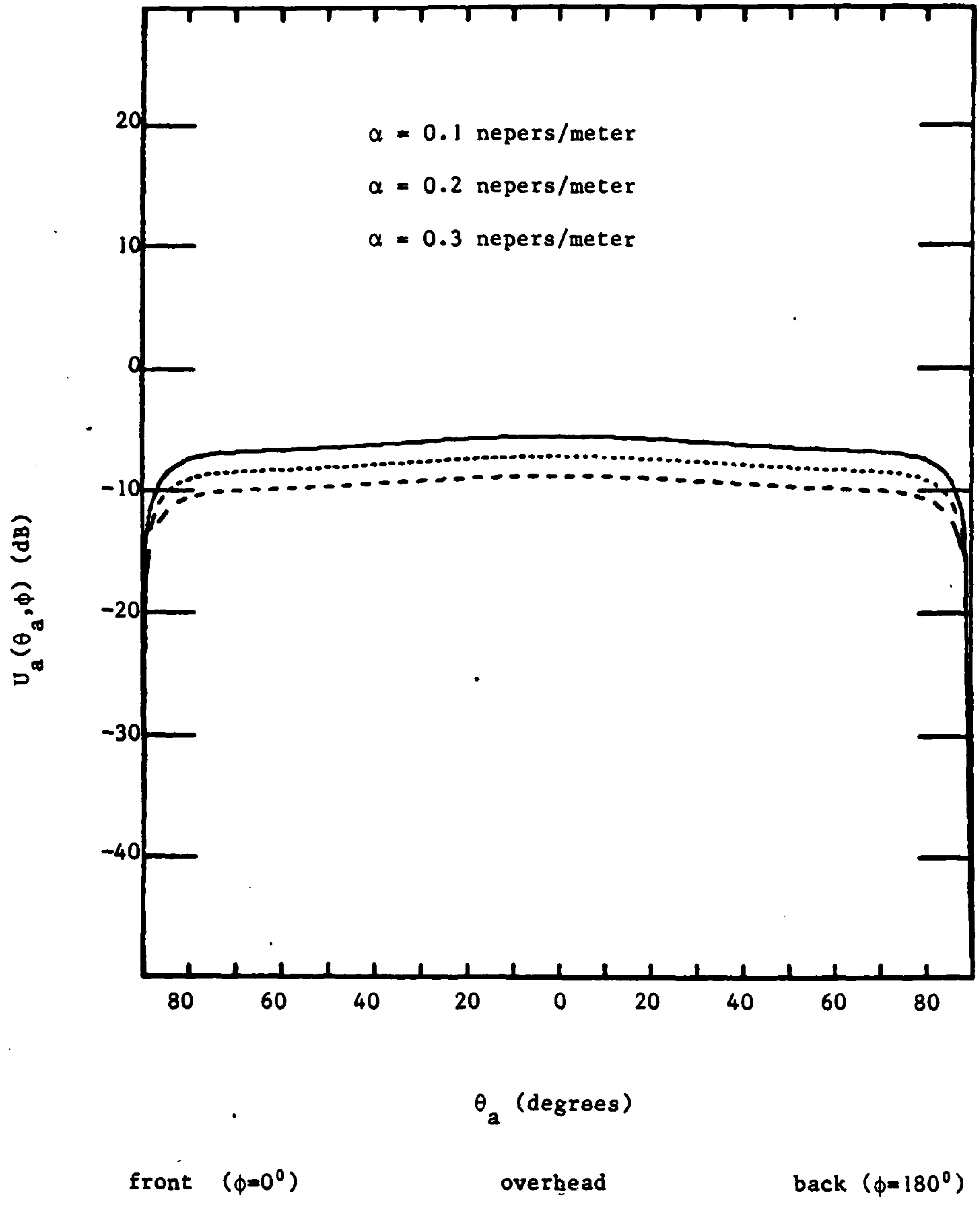

Figure IV-3. Calculated Pattern for the Buried HED With Different Antenna Attenuation Coefficients (ϵ_r = 9.0)

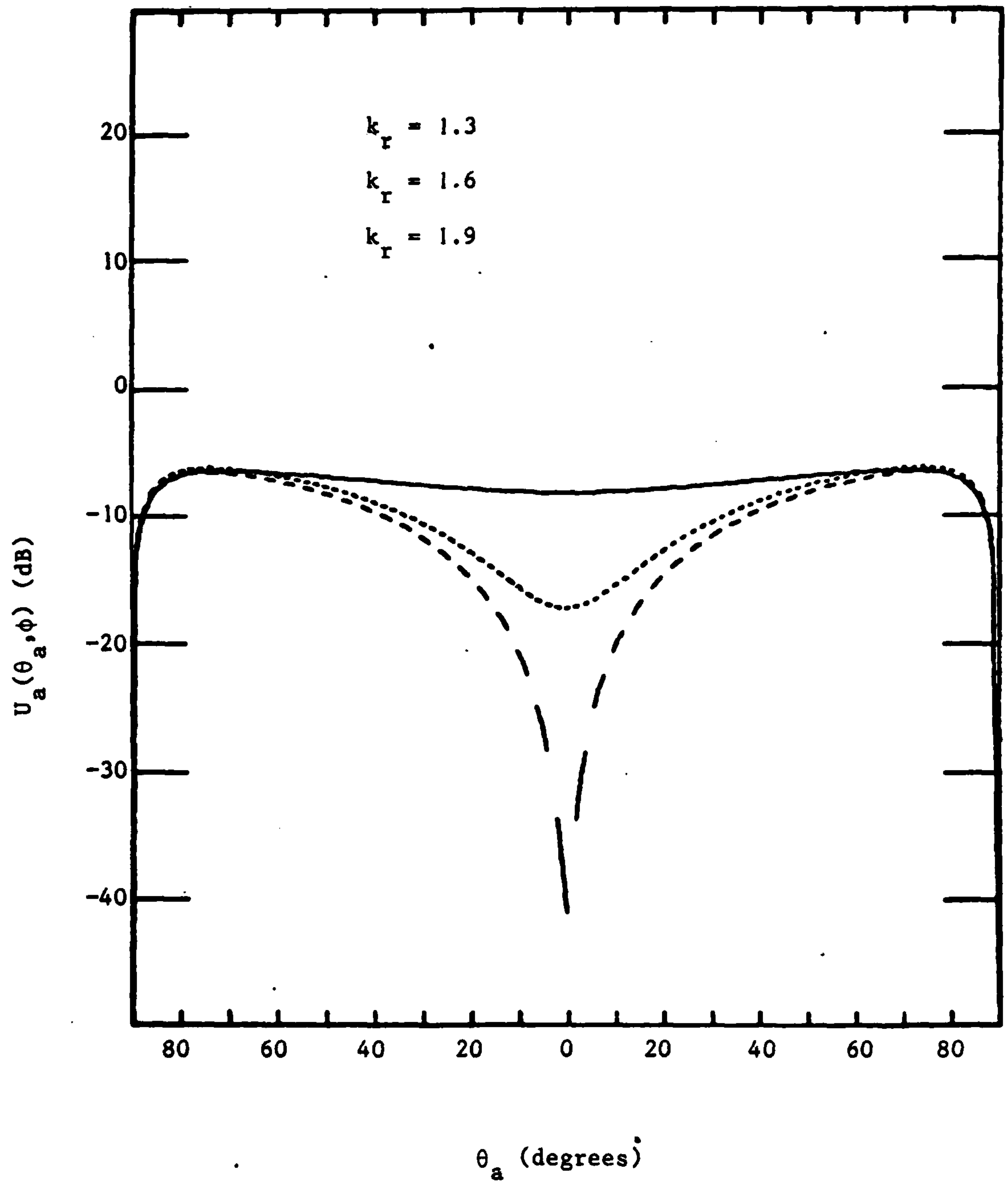

Figure IV-4. Calculated Pattern for the Buried HED With Different Antenna Propagation Constants ($\varepsilon_r = 9.0$).

Directivity and Gain

It is more desirable to plot the directivity or gain rather than just the pattern. That would mean that the whole pattern would be shifted up or down according to the total amount of power radiated or used. The directivity is given by

$$D(\theta,\phi) = \frac{U(\theta,\phi)}{U_{ave}} \tag{4-6}$$

where

$$U_{ave} = \frac{1}{4\pi} P_{radiated} = \frac{1}{4\pi} \quad U(\theta,\phi)\ d\Omega \tag{4-7}$$

To find the total radiated power, the whole pattern must be known. That includes the radiation intensity in the ground that results not only from direct radiation from the antenna, but also reflections from the interface. Then the whole pattern would have to be integrated numerically. An analytic integration would be even more complex - if it could be done at all.

The gain is given by

$$G(\theta,\phi) = \frac{U(\theta,\phi)}{\frac{1}{4\pi} P_{in}} \tag{4-8}$$

where P_{in} is the total power input at the antenna terminals. Both the antenna impedance and the current must be known to find this. A current has been assumed but the impedance would depend heavily on the type of cable used, the parameters of the ground, and the depth of burial.

As a result of these problems, the patterns shown are "floating". That is, their absolute values cannot be compared, but the relative values of one pattern can be. Therefore, the numbers given for the magnitudes of the patterns show only the relative values of a pattern.

Losses

Because the soil is not a perfect dielectric, it will absorb a portion of the power as the wave propagates through. The attenuation constant for a slightly lossy dielectric is given in Ramo et al (Ref 17:335) as

$$\alpha \approx \frac{k_g \varepsilon''}{2\varepsilon'} \qquad (4\text{-}9)$$

where $\varepsilon' = \varepsilon_r \varepsilon_o$ and $\varepsilon'' = \sigma_g/\omega$. The power loss will then be

$$\gamma_1 = (\exp(-\alpha d))^2 = \left(\exp(-\frac{k_g \sigma_g}{2\omega\varepsilon_g\varepsilon_o}\frac{h}{\cos\theta_g})\right)^2 \qquad (4\text{-}10)$$

where $h/\cos\theta_g$ is the distance the wave travels through the ground. But for $n_g \geq 3.0$, $\cos\theta_g \approx 1$. Then, using $k_g = \sqrt{\varepsilon_g} k_o$, and $\eta_o = k_o/\omega\varepsilon_o$, equation (4-10) simplifies to

$$\gamma_1 = \exp(-\frac{\eta_o \sigma_g h}{\sqrt{\varepsilon_g}}) \qquad (4\text{-}11)$$

Table IV-1 shows the loss for the different soil parameters found in the literature.

Reference	Soil moisture content	Analysis frequency	Dielectric constant ϵ_r	Conductivity σ_g (mhos/m)	Losses (dB) burial - 0.5 m
Biggs and Swarm (Ref 3:206)	not given	LF	10	0.0005	-0.13
Entzminger *et al* (Ref 6:45-48)	wet?	10 MHz	60	0.03	-3.2
King and Shen (Ref 10:1052)	dry	144 MHz	4	0.00004	-0.01
Corvus (Ref :33)	dry	HF, VHF	9	0.001	-1.3
	wet	HF, VHF	25	0.01	-9.2
Burke *et al* (Ref :99)	dry	HF, VHF	9	0.005	-0.27
	wet	HF, VHF	20	0.05	-1.7

Table IV-1. Soil Losses at a Burial Depth of 0.5 Meters.

V. Conclusions and Recommendations

Conclusions

As stated in the introduction, a goal of this thesis was to develop a simple but accurate method to determine the far-field pattern of a buried HED. A relatively simple method has been developed, but its accuracy has yet to be determined, especially since a comparison with measurements would be required.

The literature search revealed a number of articles on the topic. Most includes assumptions so that they could not be applied to this case of a HED operated at 37.5 MHz.

The solution developed in Chapter III involves conventional antenna theory and ray-optics. It assumes the ground to be a slightly lossy dielectric, which was shown to be a fairly good approximation, depending on the moisture content of the soil. The difference between this solution and the most applicable solution from the literature is a factor of $\cos\theta_a$ where θ_a is the angle off the normal to the ground. So at least overhead, the two solutions are in agreement. Near the horizon, the difference is fairly large.

The directivity or gain was not evaluated because of the difficulty of finding the total radiated or input power. Several patterns were shown for the expected current distributions. Burial seems to lower the pattern overhead so most of the power is radiated close to the horizon. Most importantly, it was shown that the pattern is dependant on the dielectric constant of the soil and how it affects

the current distribution.

Recommendations

In order to more fully compare what happens when an antenna is buried, the program in Appendix B should be expanded to integrate the pattern over the whole sphere surrounding the antenna. This would give a value for the total power radiated, and hence, the directivity could be determined. Also it would be interesting to find out exactly what happens to the current distribution and impedance on an antenna as it is buried.

The difference between the Biggs and Swarm equation and the dielectric method should be examined to find why they are the same overhead but different at the horizon. Finally, it would be good to get Vaziri's program to work and compare those results. These tools could then be used to more effectively evaluate the buried antenna array of Part II.

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Appendix A

Vaziri's Program

```
*********************************************************
* Main program to calculate the far-field pattern       *
*  using F. Vaziri's program                            *
*      1) Reads data from 'datath'                      *
*      2) Calls Vaziri's solution for each point in the *
*             desired pattern                           *
*      3) Formats data for plotting                     *
*********************************************************
      real N,X(5,0:90),Y(5,0:90)
      data ((Y(i,j),j=0,90),i=1,5)/455*-50./
      open (1,file='datath')
           rewind 1

      read(1,1) Nplots,Id
1          format(2i3)
30    write(6,2) Id, Nplots
2          format(/////'#',i2,5x,i3,' plots')

      write(6,3)
3     format(// plot',3x,'N',9x,'Sg',8x,'p  ')

******************************************************
* do loop to plot different cases on the same graph *
******************************************************

      do 10 Ip=1, Nplots

      read(1,4) N,p,Sg
4     format(3f10.5)

      write(6,5) Ip,N,Sg,p
5     format(i2,5f10.3,2i10)

******************************************
* do loop to vary XI from 0-90 degrees *
******************************************
50    do 20 IXI=5,85,5
      XId=IXI+.0001

      call Pviz(XId,N,Sg,Pw,p)

      Y(Ip,IXI)=Pw
      X(Ip,IXI)=XId
```

```
      if(Pw.ge.1e3)goto 10

20    continue
10    continue

      write(6,8)
8     format(//15x,'1',9x,'2',9x,'3',9x,'4',9x,'5')
      write(6,9) (X(1,l),(Y(j,l),j=1,5),l=0,90,5)
9     format(6f10.3)

      read(1,1) Nplots,Id
      if(Id.ne.0)goto 30

      stop
      end
```

```
      subroutine Pviz(XId,N,Sg,Pw,p)
************************************************************
* this subroutine calculates the far-field radiation intensity *
*  using a modified program from a dissertation by F. Vaziri.  *
************************************************************

*****************************************
* Input from main program               *
*     XId  angle off horizon (degrees)  *
*     N    index of refraction for ground *
*     Sg   conductivity of the ground   *
*     p    distance from antenna        *
* Output                                *
*     Pw  radiation intensity           *
*****************************************
      real N
      DIMENSION INDEX(6)
      COMMON NN,NX,XNEAR,XINTER,XFAR
      COMMON /BLK1/H,Z,FQ,ER1,SIG1,MU1,ER2,SIG2,MU2,SIGN,R,W2MUO,EOI
      common /b4/Eint

************************************************
* INDEX indicates which polarization           *
* H      burial depth                          *
* FQ     operating frequency                   *
************************************************
      data PI/3.1415926536/
      DATA INDEX/0,0,1,0,0,0/
      DATA H,FQ/.175,144.E6/

**********************************************************
* ER1, SIG1  dielectric constant and conductivity of the  *
*   half-space that includes the antenna                  *
* ER2, SIG2  dielectric constant and conductivity of the  *
*   half-space opposite the antenna                       *
**********************************************************
      ER1=N*N
      SIG1=Sg
      DATA ER2,SIG2/1.0,0.0/

      CALL CONST

**********************
* convert deg to rad *
**********************
      XIr=XId*PI/180.

***************************************
* Z   vertical observation distance    *
* R   horizontal observation distance  *
*      the cordinate system is upside- *
*      down because H must be positive *
```

```
*******************************************
      Z=-p*sin(XIr)
      R=p*cos(XIr)


      DO 4 NN=1,6
4     CALL COMP(INDEX(NN))

**********************************
*  calculate radition intensity *
**********************************
      Pw=Eint*Eint/(2*377)

6     return
      END
%
```

```
      SUBROUTINE CONST
C        THIS SUBROUTINE CALCULATES NECESSARY CONSTANTS.
      COMMON /BLK1/H,Z,FQ,ER1,SIG1,MU1,ER2,SIG2,MU2,SIGN,R,W2MUO,EO
      COMMON /BLK2/W,KO,N1SQ,N2SQ,E1,E2,K1,K2,K1S,K2S,N,CSIG,POLE,P
     C               MUO,EO,ABSN
      COMMON /BLK4/AI,AIK1,AIK2
      COMMON /BLK6/ KR,E1INV
      COMPLEX N1SQ,N2SQ,E1,E2,N1,N2,K1,K2,N,CSIG ,K1S,K2S

      COMPLEX KR,E1INV

      REAL KO,MUO,MU1,MU2

      EO=8.854E-12
      MUO=1.257E-06
      PI=3.14159

C       MU1 AND MU2 ARE RELATIVE PERMEABILITIES OF MEDIUM 1 AND 2

      MU1=1.
      MU2=1.

      IF(Z) 1,2,2
1     SIGN=-1
      GO TO 3
2     SIGN=1.
3     CONTINUE

      W=2.*PI*FQ
      C=1./(EO*MUO)**.5
      W2MUO=W*W*MUO
      EOINV=1./EO
      KO=W/C

      N1SQ=CMPLX(ER1,SIG1/W/EO)
      E1=EO*N1SQ
      N1=CSQRT(N1SQ)
      K1=KO*N1
      AIK1=AIMAG(K1)
      K1S=K1*K1

      N2SQ=CMPLX(ER2,SIG2/W/EO)
      E2=EO*N2SQ
      N2=CSQRT(N2SQ)
      K2=KO*N2
      AIK2=AIMAG(K2)
      K2S=K2*K2
```

```
E1INV=1./E2
KR=E1/E2
N=K2/K1
ABSN=CABS(N)
CSIG=CMPLX(SIG1,-EO*W)
POLE=AIMAG(CSQRT((E2*E2*K1S-E1*E1*K2S)/(E2*E2-E1*E1)))

RETURN
END
```

```
      SUBROUTINE COMP(INDEX)
C       THIS SUBROUTINE EVALUATES THE FIELD COMPONENT IF INDEX NE 0

      COMMON NN,NX,XNFAR,XINTER,XFAR
      COMMON /BLK1/H,Z,FQ,ER1,SIG1,MU1,ER2,SIG2,MU2,SIGN,R,W2MUPO,E
      COMMON /BLK2/W,K0,N1SQ,N2SQ,E1,E2,K1,K2,K1S,K2S,N,CSIG,POLE,P
C                 MU0,E0,ABSN
      COMMON /BLK3/CONST
      COMMON /BLK4/AI,AIK1,AIK2
      COMMON /BLK5/IFLG1,IFLG2
      common /b4/Eint

      COMPLEX N1SQ,N2SQ,E1,E2,K1,K2,N,CSIG,K1S,K2S
      COMPLEX I1,I2,I,CONST

      REAL K0,MU0

      IF (INDEX.EQ.0) GO TO 5
      IFLG1=0
      IFLG2=0
      EPS=0.
      I1=(0.,0.)
      I2=(0.,0.)
      START=0.
      END=.99*POLE

C       INTEGRATE FROM 0 TO THE VICINITY OF THE POLE

      CALL AUTO(START,END,EPS,I1,I2)
      START=END
      END=1.005*POLE

C       INTEGRATE ON THE POLE

      CALL AUTO(START,END,EPS,I1,I2)
      START=END
      END=1.015*POLE
      IFLG1=0
      IFLG2=0
      CALL AUTO(START,END,EPS,I1,I2)
      IFLG1=0
      IFLG2=0
      START=END

C       CONTINUE INTEGRATION

      DO 2 J=1,41,4
      AJ=J
```

```
      END=POLE*(2.**AJ)
C       TERMINATE INTEGRATION IF INTEGRAND IS NEGLIGIBLE
      IF (IFLG1+IFLG2-2) 1,3,3
1     CALL AUTO(START,END,EPS,I1,I2)
2     START=END
3     CONTINUE
      I=I1+I2
      Eint=cabs(I*CONST)

5     RETURN
      END
%
```

```
      SUBROUTINE AUTO(START,END,EPX,I1,I2)

C       THIS SUBROUTINE PERFORMS NUMERICAL INTEGRATION ALONG VERTIC
C         BRANCH CUTS.

      COMMON NN,NX
      COMMON /BLK1/H,Z,FQ,ER1,SIG1,MU1,ER2,SIG2,MU2,SIGN,R,W2MUO,EO
      COMMON /BLK4/AI,AIK1,AIK2
      COMMON/BLK5/IFLG1,IFLG2

      COMPLEX I1,I2,T1,T2,CSIQD,FNC

      EXTERNAL FNC

C       ETA IS INTEGRATION ERROR

      ETA=.01
      NX=1
      AI=AIK1
      IF((Z+H).LT.0.)  NX=3

C       TERMINATE INTEGRATION ALONG BRANCH CUT 1 IF INTEGRAND TOO S

      IF (IFLG1.EQ.1) GO TO 1
      T1=CSIQD(START,END,FNC,EPX,ETA)
      I1=I1+T1
      IF (CABS(T1). LT.CABS(I1)*.01) IFLG1=1
1     CONTINUE

      NX=NX+1
      AI=AIK2

C       TERMINATE INTEGRATION ALONG BRANCH CUT 2 IF INTEGRAND TOO S

      IF (IFLG2.EQ.1) GO TO 2
      T2=CSIQD(START,END,FNC,EPX,ETA)
      I2=I2+T2
      IF (CABS(T2).LT.CABS(I2)*.01) IFLG2=1
2     CONTINUE
      EPX=CABS(I1+I2)*.001
      RETURN
      END
%
```

```
      COMPLEX FUNCTION FNC(X)

C       THIS FUNCTION SUBPROGRAM EVALUATES THE NUMERICAL VALUE OF TH
C       INTEGRAND.  WHEN ARGUMENT IS ZERO, IT ALSO CALCULATES
C       CORRESPONDING BANOS'S APPROXIMATIONS.

      dimension JFLG(6)

      COMMON NN,NX,XNEAR,XINTER,XFAR
      COMMON /BLK1/H,Z,FQ,ER1,SIG1,MU1,ER2,SIG2,MU2,SIGN,R,W2MUO,EOI
      COMMON /BLK2/W,KO,N1SQ,N2SQ,E1,E2,K1,K2,K1S,K2S,N,CSIG,POLE,PI
     C           MUO,EO,ABSN
      COMMON/BLK3/CONST
      COMMON /BLK4/AI,AIK1,AIK2
      COMMON /BLK6/ KR,E1INV

      COMPLEX KR,KRA2,KRB2,E1INV
      COMPLEX N1SQ,N2SQ,E1,E2,K1,K2,N,CSIG,K1S,K2S
      COMPLEX B1,B2,L,ARG,EXP1,EXP2,FRAC1,FRAC2,A1,A2
      COMPLEX XFRAC1,XFRAC2,CONST
      complex T
      COMPLEX HONEO,HONE1
      COMPLEX HO,H1,H1D,FX1,FX2

      REAL KO,MUO,MU1,MU2

      DATA JFLG/1,1,0,1,1,-1/


      IF(X.GT.1.E-30) GO TO 1
      FNC=(0.,0.)

C       CALCULATE OBSERVER HEIGHT FOR BANOS'S APPROXIMATIONS.

      Z1=Z-H

C       SKIP BANOS'S APPROXIMATIONS IF SOURCE DIPOLE IS IN AIR

      IF (ABSN.GT.1.) GO TO 180
      T=(0.,1.)*N*CSQRT(.5*PI*(0.,1.)*K2*R)
180   IF((Z+H).LT.0.) GO TO 72
1     IF (R*(AI+X).LE.20.) GO TO (3,4,6,7),NX
      FNC=(0.,0.)
      RETURN

C       EVALUATE FIELD INTEGRAL ALONG BRANCH CUT 1 FOR POINTS OF
C       OBSERVATION IN MEDIUM

3     B1=CSQRT(X*X-(0.,2.)*K1*X)
```

```
      print*,'at 3'
      B2=CSQRT(K2S-K1S+X*X-(0.,2.)*K1*X)
      L=K1+(0.,1.)*X

C       USE MODIFIED FORMULAS IF SOURCE DIPOLF IN AIR

      IF (ABSN.GT.1.) B2=-B2
      EXP1=CEXP((0.,-1.)*B1*SIGN*Z)
      EXP2=CEXP((0.,1.)*B1*(Z+2.*H))
      KRB2=KR*B2
      ARG=L*R
      IF (JFLG(NN)) 200,210,220
220   H0=HONE0(ARG)
      H1=HONE1(ARG)
      H1D=H0-H1/ARG
      FRAC1=(B1+B2)/(B1-B2)
      FX1=FRAC1*EXP2
210   FRAC2=(B1+KRB2)/(B1-KRB2)
      FX2=FRAC2*EXP2
      GO TO 230
200   FRAC1=(B1+B2)/(B1-B2)
      FX1=FRAC1*EXP2
230   continue

C       EVALUATE FIELD INTEGRAL ALONG BRANCH CUT 2 FOR POINTS OF
C       OBSERVATION IN MEDIUM 1

4     A1=CSQRT(K1S-K2S+X*X-(0.,2.)*K2*X)
      print*,'at 4'
      A2=CSQRT(X*X-(0.,2.)*K2*X)
      L=K2+(0.,1.)*X

C       USE MODIFIED FORMULAS IF SOURCE DIPOLE IN AIR

      IF (ABSN.GT.1.) A1=-A1
      EXP2=CEXP((0.,1.)*A1*(Z+2.*H))
      KRA2=KR*A2
      ARG=L*R
      IF(JFLG(NN)) 300,310,320
320   H0=HONE0(ARG)
      H1=HONE1(ARG)
      H1D=H0-H1/ARG
      FRAC1=(A1+A2)/(A1-A2)
310   FRAC2=(A1+KRA2)/(A1-KRA2)
      GO TO 330
300   FRAC1=(A1+A2)/(A1-A2)
330   continue

C       EVALUATE FIELD INTEGRAL ALONG BRANCH CUT 1 FOR POINTS OF
C       OBSERVATION IN MEDIUM 2

6     B1-CSQRT(X*X-(0.,2.)*K1*X)
      B2=CSQRT(K2S-K1S+X*X-(0.,2.)*K1*X)
```

```
      L=K1+(0.,61.)*X
      L=K1+(0.,1.)*X
C       USE MODIFIED FORMULAS IF SOURCE DIPOLE IN AIR
      IF (ABSN.GT.1.) B2=-B2
      EXP1=CEXP((0.,1.)*B1*H)
      EXP2=CEXP((0.,1.)*B2*(7+H))
      KRB2=KR*B2
      ARG=L*R
      IF (JFLG(NN)) 400,410,420
420   H0=HONE0(ARG)
      H1=HONE1(ARG)
      H1D=H0-H1/ARG
      FRAC1=1./(B1+B2)
      FRAC2=1./(B1-B2)
410   XFRAC1=E1INV/(B1+KRB2)
      XFRAC2=E1INV/(B1-KRB2)
      GO TO 430
400   FRAC1=1./(B1+B2)
      FRAC2=1./(B1-B2)
430   GO TO 70
C       EVALUATE FIELD INTEGRAL ALONG BRANCH CUT 2 FOR POINTS OF
C       OBSERVATION IN MEDIUM 2
7     A1=CSQRT(K1S-K2S+X*X-(0.,2.)*K2*X)
      A2=CSQRT(X*X-(0.,2.)*K2*X)
      L=K2+(0.,1.)*X
C       USE MODIFIED FORMULAS IF SOURCE DIPOLE IN AIR
      IF (ABSN.GT.1.) A1=-A1
      EXP1=CEXP((0.,1.)*A1*H)
      EXP2=CEXP((0.,1.)*A2*(Z+H))
      KRA2=KR*A2
      ARG=L*R
      IF(JFLG(NN)) 500,510,520
520   H0=HONE0(ARG)
      H1=HONE1(ARG)
      H1D=H0-H1/ARG
      FRAC1=1./(A1+A2)
      FRAC2=1./(A1-A2)
510   XFRAC1=E1INV/(A1+KRA2)
      XFRAC2=E1INV/(A1-KRA2)
      GO TO 530
500   FRAC1=1./(A1+A2)
      FRAC2=1./(A1-A2)
530   GO TO 71
C       ***********************************************************
C                                    HED Ez2
C       ***********************************************************
```

```
70    FNC=L*L*HONE1(ARG)*EXP2*B1*(XFRAC1/EXP1-XFRAC2*EXP1)
      RETURN

71    FNC=L*L*HONE1(ARG)*A1*EXP1*(XFRAC2*EXP2-XFRAC1/EXP2)
      RETURN
72    CONST=1./(4.*PI*W)
      IF(ABSN.GT.1.) RETURN

      XNEAR =CABS(K1/(2.*PI*CSIG*R*R))
      XINTER=CABS(K2*K2/(2.*PI*CSIG*R)/N*(1.+T))
      XFAR  =CABS(K1/(2.*PI*CSIG*N*N*R*R))

      RETURN
      END
%
```

```
      COMPLEX FUNCTION CSIQD(A,B,FCN,EPS,ETA)
C       ROMBERG INTEGRATION FOR COMPLEX FUNCTION WITH REAL
C       ARGUMENT, MODIFIED
      COMPLEX FCN,Q(11),T,SUM,FCNXI,QX1,QX2
      EXTERNAL FCN
      H=(B-A)/2.
      T=H*(FCN(A)+FCN(B))
      NX=2
      DO 12 N=1,10
      SUM=0.
      DO 2 I=1,NX,2
      FCNXI=FCN(A+FLOAT(I)*H)
2     SUM=SUM+FCNXI
      T=T/2.+H*SUM
      Q(N)=(T+H*SUM)/1.5
      IF(N-2) 10,3,3
3     F=4.
      I=N
      DO 4 J=2,N
      I=I-1
      F=F*4.
4     Q(I)=Q(I+1)+(Q(I+1)-Q(I))/(F-1.)
      IF(N-3)9,6,6
6     X1=ABS(REAL(Q(1)-QX2))+ABS(REAL(QX2-QX1))
      X2=ABS(AIMAG(Q(1)-QX2))+ABS(AIMAG(QX2-QX1))
      TABS1=ABS(REAL(Q(1)))
      TABS2=ABS(AIMAG(Q(1)))
      IF(TABS1)7,8,7
7     IF(X1/TABS1-ETA)20,20,8
8     IF(X1-EPS)20,20,9
20    IF(TABS2)71,81,71
71    IF(X2/TABS2-ETA)11,11,81
81    IF(X2-EPS)11,11,9
9     QX1=QX2
10    QX2=Q(1)
      H=H/2.
12    NX=NX*2
      WRITE(6,100) A,B
100   FORMAT(43H ACCURACY LESS THAN SPECIFIED VALUES--CSIQD 2E11.4)
11    CSIQD=Q(1)
      RETURN
      END
```

```
%

      COMPLEX FUNCTION HONEO(XZ)
C       HANKEL FUNCTION OF FIRST KIND, ORDER 0, IMAGINARY PART LT 30
      IMPLICIT COMPLEX (X)
      AIXZ=AIMAG(XZ)
      IF(AIX7.GT.20.) GO TO 81
      XW=-XZ*XZ/4.
      PI=3.141592653589
      TPI=2.*PI
      XI=(0.,1.)
      IF(CABS(XZ).GT.5.) GO TO 7
      FAC=0.
      XFAC=(1.,0.)
      XSUMY=(0.,0.)
      XSUMJ=(1.,0.)
      DO 5 I=1,50
      AI=I
      FAC=FAC+1./AI
      XFAC=XFAC*XW/(AI*AI)
      XTE=FAC*XFAC
      XSUM7=XSUMY+XTE
      XSUMJ=XSUMJ+XFAC
      IF(CABS(XTE).LT.1.E-10) GO TO 6
5     CONTINUE
      WRITE(6,92)XZ,XTE,XFAC
92    FORMAT(5X,'HONEO SUM EXCEEDS 50 TERMS',6E15.3//)
      HONEO=(0.,0.)
      RETURN
6     XJ=XSUMJ
      HONEO=XJ+XI*(2./PI)*((CLOG(XZ/2.)+.5772156649)*XJ-XSUMY)
      RETURN
7     XP=1.-(9./(128.*XZ*XZ))*(1.-1225./(768.*XZ*XZ))
      XQ=-(1./(8.*XZ))*(1.-225./(384.*XZ*XZ))
      RZ=REAL(XZ)
      SIGN=1.
      IF(RZ.LT.0.)SIGN=-1.
71    IF(ABS(RZ).LT.TPI) GO TO 73
72    RZ=RZ-SIGN*TPI
      GO TO 71
73    HONEO=(XP+XI*XQ)*(COS(RZ-.25*PI)+XI*SIN(RZ+.25*PI))
     1      *EXP(-AIXZ)*CSQRT(2./(PI*XZ))
      RETURN
81    HONEO=(0.,0.)
      RETURN
      END
%
```

```
      COMPLEX FUNCTION HONE1(XZ)
C       HANKEL FUNCTION OF FIRST KIND, ORDER 1, IMAGINARY PART LT 30
      IMPLICIT COMPLEX(X)
      AIXZ=AIMAG(XZ)
      IF(AIXZ.GT.20.) GO TO 81
      XW=-XZ*XZ/4.
      PI=3.141592653589
      TPI=2.*PI
      XI=(0.,1.)
      IF(CABS(XZ).GT.5.) GO TO 7
      FAC=-.5772156649
      XFAC=(1.,0.)
      XSUMY=FAC+.5
      XSUMJ=(1.,0.)
      DO 5 I=1,50
      AI=I
      FAC=FAC+1./AI
      XFAC=XFAC*XW/(AI*(AI+1.))
      XTE=(FAC+.5/(AI+1.))*XFAC
      XSUMY=XSUMY+XTE
      XSUMJ=XSUMJ+XFAC
      IF(CABS(XTE).LT.1.E-10) GO TO 6
5     CONTINUE

      WRITE(6,92)XZ,XTE,XFAC

92    FORMAT(5X,'XHFR1 SUM EXCEEDS 50 TERMS',6E15.3//)
      HONE1=(0.,0.)
      RETURN
6     XJ=XSUMJ*XZ/2.
      HONE1=XI*((CLOG(XZ/2.)*XJ-1./XZ)*(2./PI)-XZ*XSUMY/PI)+XJ
      RETURN
7     XP=1.+(15./(128.*XZ*XZ))*(1.-315./(256.*XZ*XZ))
      XQ=(3./(8.*XZ))*(1.-35./(128.*XZ*XZ))
      RZ=REAL(XZ)
      SIGN=1.
      IF(RZ.LT.0.)SIGN=-1.
71    IF (ABS(RZ).LT.TPI) GO TO 73
72    RZ=RZ-SIGN*TPI
      GO TO 71
73    HONE1=(XP+XI*XQ)*(COS(RZ-.75*PI)+XI*SIN(RZ-.75*PI))*
     cEXP(-AIXZ)*CSQRT(2./(PI*XZ))
      RETURN
81    HONE1=(0.,0.)
      RETURN
      END
%
```

Appendix B

Dielectric Method Program

```
      program vertic

*******************************************************************
* Main program used to calculate the far-field pattern            *
* of a horizontal electric dipole.                                *
*    1)  Reads data for current distribution and soil parameters  *
*    2)  Calls Uff subroutine to calculate the radiation          *
*              intensity at each point in the pattern.            *
*    3)  Formats data for plotting                                *
*          (plotting subroutine not shown)                        *
*******************************************************************

      real N,Kr,X(5,0:180),UdB(5,0:180),U(2)
      common /b1/ALP,Kr,shift
      data PI/3.1415926536/

      open (1,file='datath')
           rewind 1

      read(1,1) Nplots,Id
1          format(2i3)

      open(2,file='outth')
30    write(2,2) Id, Nplots
2          format(/////'#',i2,5x,i3,' plots')

      write(2,3)
3     format(/' plot',6x,'Meth',6x,'J',9x,'N',9x,'B',9x,'ALP',7x
     c,'Kr',8x,'PHId',8x,'shift'/)

*****************************************************
* initialize                                        *
*    UdB  power density pattern (in dB's),          *
*    Gerr greatest integration error per graph      *
*****************************************************
      do 50 i=0,180
      do 50 j=1,5
      UdB(j,i)=0.
50    continue
      Gerr=1e-5

*****************************************************
* do loop to plot different cases on the same graph *
*****************************************************
      do 10 Ip=1, Nplots

      read(1,4) Meth,J,N,B,ALP,Kr,PHId,shift
4     format(2i3,6f10.5)

      write(2,5) Ip,Meth,J,N,B,ALP,Kr,PHId,shift
```

```
5     format(i5,2i10,6f10.3)

******************************************************
* do loop to vary XId (the angle off the horizon)   *
*    from 0-90 degrees  for the front lobe and then *
*    90-0 degrees for the back lobe                 *
******************************************************
      do 20 IXId=0,180
      XId=IXId+.0001
      if (IXId.gt.90) then
         PHId=180.
         XId=180-IXId+.0001
         end if

      call Uff(PHId,XId,N,J,B,Err,U(1),U(2))

      UdB(Ip,IXId)=10.*alog10(U(Meth)+1e-5)
      X(Ip,IXId)=IXId

      if(Err.gt.Gerr) Gerr=Err
20    continue
10    continue


      write(2,11) GERR
11    format(' greatest integration error=',f10.5///)

**************************************************************
* MPLOTS  plotting subroutine                                *
* HDCOPY  transfers plot to paper using Textronix 4631      *
*               Hard Copy Unit                               *
**************************************************************

      call MPLOTS(5,181,X,UdB,UdBmax)

      write(6,6) Id
6     format(i3)
      call HDCOPY

*******************************
* test for next set of data   *
*******************************

      read(1,1) Nplots,Id
      if(Id.ne.0)goto 30


40    stop
      end
%
```

```
      subroutine Uff(PHId,XId,Ng,J,B,Err,Upd,Ubs)

*****************************************************************
* Input                                                         *
*    B    length of antenna (meters)                            *
*    PHId azimuthal angle (degrees)                             *
*    J    polarization index                                    *
*            J=1 for theta polarization                         *
*            J=2 for horizontal '                               *
*    XId  angle off horizon (degrees)                           *
*    Ng   index of refraction for ground                        *
* Output                                                        *
*    Upd  radiation intensity (perfect dielectric method)       *
*    Ubs  radiation intensity (Biggs and Swarm method)          *
*    Err  max integration error per case                        *
* Output to INT                                                 *
*    THa,PHIr                                                   *
*****************************************************************

      external INT
      common /b2/THa,PHIr
      real Ng,Na,E(2),Ko
      complex CDM

*********************************************
* Na   index of refraction in air           *
* FQ   operating frequency                  *
* Eo   permittivity of free space           *
* C    speed of light (m/s)                 *
* W    radial frequency                     *
* Ko   propagation coefficient of free space *
* ETAo intrinsic impedance of free space    *
*********************************************
      data Na,PI,FQ,Eo,C/1.0,3.1415926536,37.5e6,8.854e-12,3e8/
      W=2*PI*FQ
      Ko=W/C
      ETAo=377.

****************************
* convert deg to rad       *
****************************
      PHIr=PHId*PI/180.
      XIr=XId*PI/180.

**************************************
* snell's law .                      *
*   THa   angle from norm in air     *
*   THg   angle from norm in ground  *
**************************************
      THa=PI/2-XIr
```

```
      THg=asin(Na*sin(THa)/Ng)

********************************
* transmission coefficients    *
*  TT  theta polarization      *
*  TH  horizontal polarization *
********************************
      TT=2.*Ng*cos(THg)/(Ng*cos(THa)+Na*cos(THg))
      TH=2.*Ng*cos(THg)/(Ng*cos(THg)+Na*cos(THa))

**********************************
* integrate to find dipole moment *
*   DM - dipole moment           *
**********************************
      A=0.
      call INTEG(CDM,A,B,INT,Err)
      DM=cabs(CDM)


******************************
* Perfect dielectric method  *
*   E fields ( *r )          *
*     E(1)   theta pol.      *
*     E(2)   horizontal pol. *
******************************

      E(1)=30.*Ko*TT*DM*cos(THg)*cos(PHIr)
      E(2)=30.*Ko*TH*DM*sin(PHIr)

      Upd=1/(2.*ETAo)*E(J)*E(J)*COS(THa)/COS(THg)*((Na/Ng)**2)
      Ubs=Upd*cos(THa)/cos(THg)

      return
      end
%
```

```
      SUBROUTINE INTEG(INTGRL,A,B,ARG,Errg)
C INTEGRATION SUBROUTINE

********************************************
* Input                                    *
*  A,B     endpoints
*  ARG     integrand function              *
*  Errg    greatest integration error      *
* Output                                   *
*  INTGRL value of integral                *
*  Errg                                    *
********************************************
      EXTERNAL ARG
      COMPLEX CUM,DEL,Y(5),ARG,INTGRL,YIV
      DOUBLE PRECISION RDP,XN,RANG

      RANG=B-A
      NINIT=40
      NSTEPS=NINIT
      ERROR=0.0
      ERRMUL=1.0/180.0
      DO 3 I=1,5
3     Y(I)=0.0
      CUM=0.0
      XN=2*NSTEPS
      RDP=A
      R=RDP
      Y(1)=ARG(R)
15    DO 20 I=2,5
      RDP=RDP+RANG/XN
      R=RDP
      Y(I)=ARG(R)
20    CONTINUE
25    YIV=Y(1)+Y(5)-4.0*(Y(2)+Y(4))+6.0*Y(3)
      ERROR=ERRMUL*CABS(YIV)
26    IF(ERROR.GT.Errg) Errg=ERROR
      DEL=(Y(1)+Y(5)+4.0*(Y(2)+Y(4))+2.0*Y(3))
      DEL=RANG*DEL/(3.*XN)
      CUM=CUM+DEL
      IF((R+1.0E-5).GT.B) GO TO 80
      Y(1)=Y(5)
      DO 30 I=2,5
      RDP=RDP+RANG/XN
      R=RDP
      Y(I)=ARG(R)
30    CONTINUE
      GO TO 25
80    INTGRL=CUM
      RETURN
      end
%
```

```
      COMPLEX FUNCTION INT(S)
* INTEGRAND FUNCTION

*****************************************************
* Input from INTEG                                  *
*    S   distance on antenna                        *
* Input from MAIN                                   *
*    Kr   relative propagation constant of antenna  *
*    ALP  attenuation constant of antenna           *
*    shift  phase shift for second half of array    *
* Input from method subroutine(s)                   *
*    THa  angle from the normal in air (radians)    *
*    PHIr azimuthal angle (radians)                 *
*****************************************************
      COMMON /b1/ALP,Kr,shift
      COMMON /b2/THa,PHIr
      REAL Kr,LAMo
      COMPLEX ZJ,I

******************************
* FQ   operating frequency   *
* C    speed of light        *
******************************
      data FQ,C,ZJ,PI/37.5e6,3e8,(0.,1.),3.1415926536/

****************************************
* LAMo - free space wavelength         *
* BET - antenna propagation constant   *
* BETo - free space propagation constant *
****************************************
      LAMo=C/FQ
      BET=Kr*2.*PI/LAMo
      BETo=2.*PI/LAMo

*************************************
* special instructions for the array *
*************************************
      if(S.gt.16.) then
         if(S.lt.20.) goto 10
         d=36-S
         gam=shift*PI/180.
      else
         d=S
         gam=0.
      end if

**************************
* I - CURRENT ON ANTENNA  *
**************************
      I=SIN(BET*d)*CEXP(-ALP*(16.-d)+ZJ*gam)
```

```
*******************************
* INT - DIPOLE MOMENT         *
*******************************
      INT=I*CEXP(ZJ*BETo*S*SIN(THa)*COS(PHIr))

      RETURN

10    INT=0
      return
      end
%
```

Vita

Jeffrey W. Burks was born on 28 August 1960 in Upper Sandusky, Ohio. He graduated from high school in North Robinson, Ohio in 1978 and attended the Mansfield Branch of Ohio State University in Mansfield, Ohio and Ohio University in Athens, Ohio. He received the degree of Bachelor of Electrical Engineering from Ohio University on 12 June 1982. Upon graduation, he received a commision in the USAF through the ROTC program. He entered active duty a week later as a student in the Graduate Electro-Optics program at the School of Engineering, Air Force Institute of Technology.

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Part I: A method was developed to find the far-field radiation attern of a buried horizontal electric dipole (HED) at 37.5 MHz. The imaginary part of the index of refraction was shown to be negligible for dry soil at this frequency so standard antenna theory and ray-optic theory were used. The effect of the ground-air interface was modeled using the transmission coefficient and Snell's law for a dielectric interface. Because the current distribution for the buried HED depends on antenna construction, results are shown for the far-field pattern in the air for different current distributions on the HED.

The literature on this problem was reviewed; most used the Sommerfeld or moment methods to make the same calculations. The results of one of the reports using the Sommerfeld method could be compared and were found to be similar. An extensive bibliography is included.

Part II: The analysis was then applied to a buried antenna array. The current distribution was known and was used to calculate the far-field pattern. It was concluded that the far-field pattern is highly dependant on the current distribution. This part is classified.

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